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Focal point tracking system for concentration solar power collection

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ABSTRACT

This paper proposes a novel concentration solar collector. Instead of rotating a heavy concentrating lens, the proposed system moves the photo transducer. The design requires no exposed moving parts that are difficult to maintain, it also consumes less power to move the light weight solar transducer. The design is also suitable for vertical applications like building walls. With the fixed concentration lens, the focal point moves along a strange curve. This paper reports the procedure to calculate the trajectory. This research then builds an experimental setup to verify the concept. The experimental results show that the proposed focal tracking system achieves comparable solar energy conversion efficiency to the conventional systems.

Contents

1. Introduction

Concentrating solar collector uses less photovoltaic material to reach high conversion efficiency and has been very popular in solar power harvesting. The concentrating solar system requires moving lenses with bulky solar tracking mechanism and is suitable only for open space applications like rooftops or open fields. Places like urban area with limited land resources are therefore not suitable for this sort of application. This paper proposes a different concept for focal tracking that uses fixed lens without exposing the moving parts. The design can suit horizontal or vertical installations and is applicable for use on the building walls available in the urban area.

The concentrating solar systems require huge focusing lens and costing tracking mechanisms. Their inherent structures also limit the application to wide open spaces. Despite all these disadvantages, the concentrating solar collectors are still desirable because high efficiency photovoltaic materials are very expensive and highly concentrated solar intensities results in higher converting efficiencies [1]. The technology for focused solar collection is well-known and a number of survey papers are already available in the literature [2,3]. Most popular solar focusing designs can be divided into line focusing and point focusing devices [4–12]. The line focusing design consists of a parabolic trough that focuses the solar beam into a long line of concentration. Kim et al. [6]

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offered a very nice way of evaluating the thermal performances for parabolic trough, and Sendhil Kumar and Reddy [8] offered a comparison among the solar dish collectors. The point focusing design, on the other hand, focuses the solar beam into a signal point where very high temperature can be reached [9]. Active solar tracking typically improves on solar collector efficiency [2,3,10]. The alt-azimuth tracking suitable for the disc collectors requires the collector to track in both altitude and azimuth while the one axis tracking is used by the parabolic trough collectors. Due to the nature of the geometry any variations from these designs suffer reduced efficiency [8]. Poulek and Libra [11] used additional solar sensors to detect the orientation of the sun. The measurement by Liao [12] showed that dual axes tracking can increase energy collection efficiency by 2.6 times. On the commercial side, there are already more than 30 companies manufacture contracting PV systems [1]. The Sun Power Co. tested their system from October 1998 to October 1999 at Sunnyvale, USA to show that dual-axis tracking concentration system produces 37% more electricity over the fixed flat-plate system. The Amonix Inc. [13] demonstrated a Fresnel-lens point focus type HCPV system with 25KWp commercial module with 18.5% efficiency [14,15]. Another HCPV product by SolarSystem [16] demonstrated a DC efficiency of 19%. Poulek Solar s.r.o., on the other hand, used a special surface profile to enhance the photovoltaic modules performance by 30%, and had claimed 100% energy increase in dry, sunny climate conditions [17]. All the above systems have shown that concentrating solar collection is efficient and is reliable for use. Only in [17] did they mention the wide open space and sunny weather required for high performance operation. In other word, these systems are not suitable for urban applications where open spaces are rare.

This paper proposes a different solar concentrating and tracking configuration. Instead of the conventional moving lens design, the proposed system moves the solar converter to track the focal point. It is first established that there is still focusing effect even when the incident sun light is not perpendicular to the lens surface. As the sun moves across the sky, the focal point will move along a strange trajectory. If one can access this trajectory, then it is possible to move the transducer along the trajectory to catch the focused solar energy. The lens can then remain fixed. This concept allows the solar tracking system to have solid lens surface for easy maintenance and it is also feasible for vertical wall applications.

The following sections will first introduce the approach to obtain the focal trajectory. The next section will introduce the experiment setup to verify the focal trajectory. Section 4 will present the tracking mechanism design. Section 5 will present the experimental data to show this is a practical concept. The final section includes the conclusions suggestions for further study.

2. Focal trajectory simulation

The focal point simulation involves nonlinear optical ray simulation. Here we used the ASAP package to simulate the solar ray path and to determine the focal point position. This computation repeated for different solar elevation across the sky. Fig. 1 shows the resulting trajectories. There are multiple trajectories resulted from different number of rays in ASAP. Because ASAP traces individual ray, the computation results can change with added number of rays. Generally the results are more accurate with high number of rays. Experience told us that the surplus of collectible solar energy diminishes dramatically for tracking angle beyond 120° [17]. Thus, the simulation ran for elevation from 30° through 150°.

From the ASAP simulation results, one observes that as the sun moves from east to west the sky the focal point moves along a strange trajectory. This is the trajectory for the photo transducer to follow. It should also be noted that there is a certain position

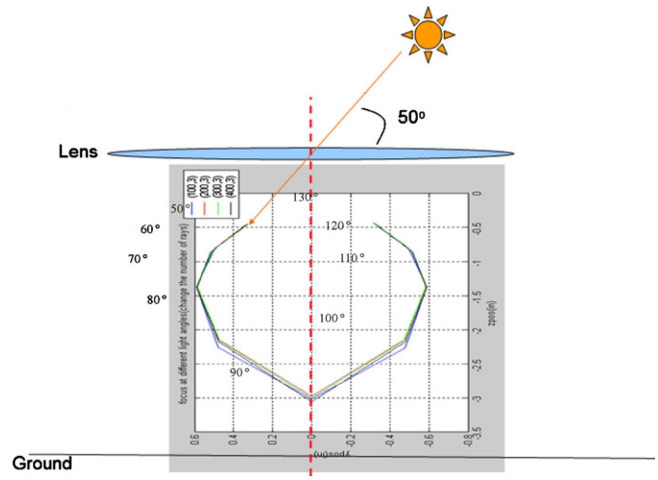

Fig. 1. Solar focal trajectory simulation.

for the transducer at a corresponding time of the day. This trajectory will have to be experimentally verified and the authors' idea is then to design a servo mechanism to automatically position the transducer at this predetermined focal position and to efficiently collect the solar energy. One slight problem with the trajectory is the concaves toward both ends of the trajectory. It turned out the tracking mechanism could block the incident beam, and we had to give up this part of the trajectory. As a result, the mechanism only tracks the trajectory from east 60° to west 120°.

3. The experimental setup

This research built a homemade solar simulator with a 500 W halogen lamp. The track mechanism is composed of two rails (Fig. 2). Notice that this is not nearly close to the actual solar irradiation in terms of the light paths and the light spectrum, but, with the limited resource, this is sufficient for our purpose. The upper rail enables the lamp to be fixed at every 5° of elevation. The lower rail allows the change of rail position to emulate seasonal solar orbit change.

The solar transducer used in this experiment was a No. CZSC2025SC010A2Z GaAs multijunction solar cell from Millennium Communication Co. Ltd. The solar cell is $10 \times 10\,mm^2$ in area to fit the focal area from the focusing lens and is $300 \pm 20\,\mu m$ thick (Fig. 3). Typical efficiency is 23% at AM 1.5 ($100\,mW/cm^2$) 25 °C. To direct electricity from the cell, it is necessary to mount the cell on a base. In this case, we fabricated two nickel padding on a wafer substrate 4 as the conductor and mount the photo transducer on top as shown in Fig. 4. The actual test piece is shown in Fig. 5.

The focusing lens is a Fresnel lens from Edmund Optics with stock no. W32-593. The lens area is $6.7 \times 6.7\,in^2$ with transmission efficiency of 92% from 400 to 1100 nm. The pyranometer in the experiment is an E20 Silicon Pyranometer from Jauntering International Co. with a resolution of $48\,\mu V/W/m^2$.

4. Tracking mechanism design

4.1. Suitable lens size

To determine a suitable size for the $10 \times 10\,mm^2$ GaAs solar cell, the authors have conducted experiments on lenses with different areas. Table 1 lists the test results. From Fig. 6 one sees that the amount of energy increases with increasing lens area but the difference became less obvious after the lens is larger than $12 \times 12\,cm^2$ and this is the size for further experiments.

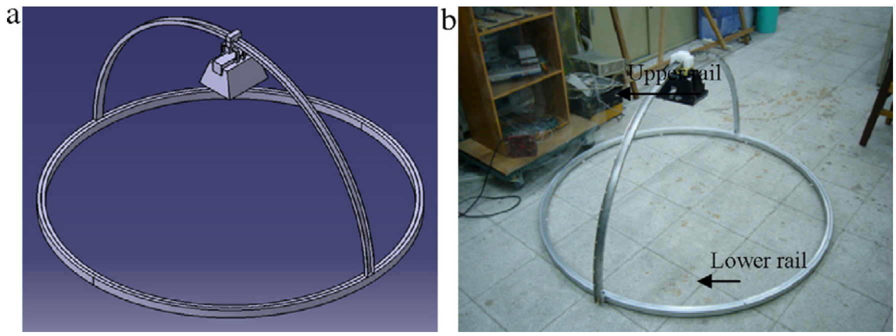

Fig. 2. (a) Solar simulator rails (drawing) and (b) actual setup.

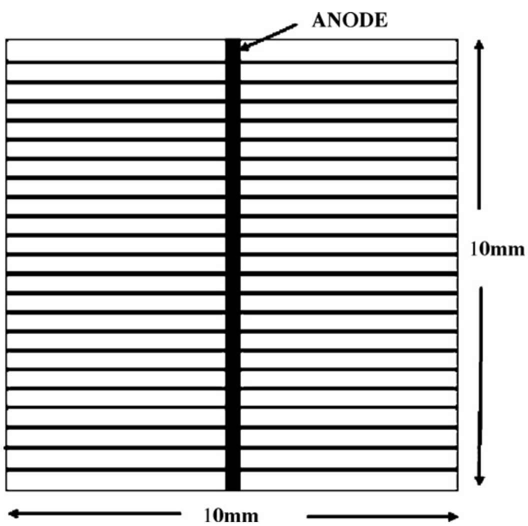

Fig. 3. $10 \times 10\,\text{mm}^2$ GaAs solar cell chip.

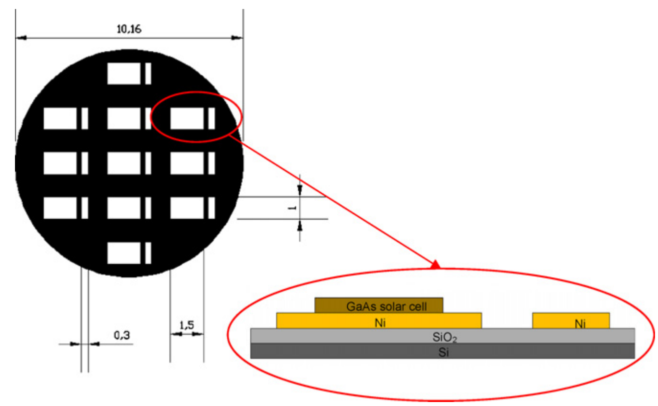

Fig. 4. The 4 inches wafer base (unit: cm) and the MEMS process.

Table 1
Energy received on the focus with lens in different sizes.

Dimension of the lens (cm)	Energy on the focus point (kW/m^2)
15.24	6.3542
12	6.1667
10	5.9167
8	5.4583
6	4.5833
4	2.3333

4.2. Simulation verification

The verification of the simulated trajectory is based on the lab built "solar simulator" with the $120 \times 120\,\text{mm}^2$ Fresnel lens. Table 2 lists the experimental results and Fig. 7 plots the trajectory. The measured trajectory is basically the same with the simulation result. This research can then proceed to build an outdoor test setup.

4.3. Mechanism design – the focal tracking concentrating solar collector

The outdoor solar collecting test module used the experimentally measured focal trajectory from Fig. 7 as reference. The concept is based on a servo control mechanism to drive the photo transducer along a predefined trajectory. Shown in Fig. 8, the trajectory is manufactured by machining a slot out of an aluminum frame and by fitting in it a pin that will carry the photo transducer.

Fig. 9 shows the focal tracking solar collector assembly. A stepper motor drives a ball-screw/plank assembly that will in turn push the photo transducer pin along the focal trajectory. The stepper motor arrangement is shown in Fig. 9(b), and the actual solar collector assembly is shown in Fig. 10.

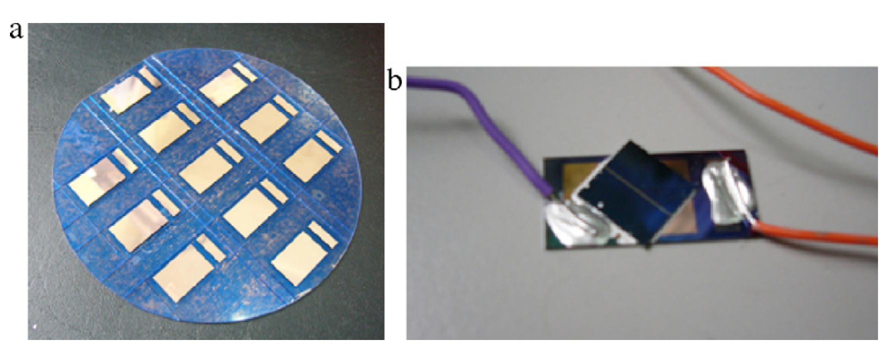

Fig. 5. (a) Actual solar cell base and (b) the completed solar cell.

Table 2
Focal positions from the test setup.

The sun in the east	5°	10°	15°	20°	25°	30°
Height (cm)	0.1	0.8	1.9	2.7	3.95	5.35
Distance (cm)	1	1.65	2.4	2.7	2.8	2.9
The sun in the west	−5°	−10°	−15°	−20°	−25°	−30°
Height (cm)	0.1	0.95	1.85	2.7	3.85	5.45
Distance (cm)	−0.85	−1.65	−2.45	−2.75	−2.85	−2.9

Table 3
Test results on the simulator.

Cell	GaAs ($10 \times 10\,mm^2$)			Si-single crystal ($176 \times 118\,mm^2$)
Tracker type	Fixed/w/o lens	Single-axis tracking w/o lens	Focal tracking (lens $120 \times 120\,mm^2$)	Single-axis tracking w/o lens
Power (kW h)	2.649×10^{-3}	2.701×10^{-3}	3.686×10^{-3}	3.654×10^{-2}
Increase ratio (10:00–14:00)	100%	102.0%	139.2%	
Power (kW h)	2.538×10^{-3}	2.706×10^{-3}	2.774×10^{-3}	3.691×10^{-2}
Increase ratio (08:00–16:00)	100%	106.7%	109.3%	

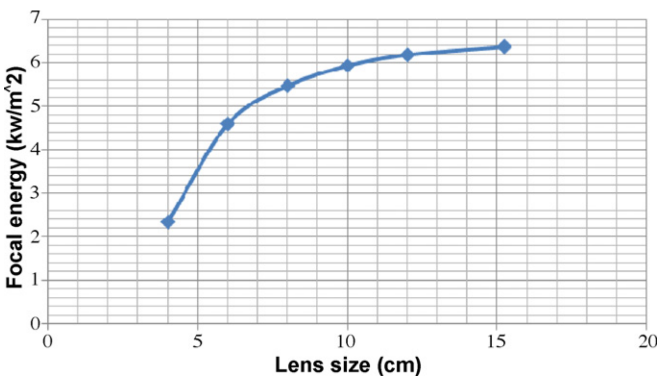

Fig. 6. The lens sizes (cm) vs. energy obtained at the focus.

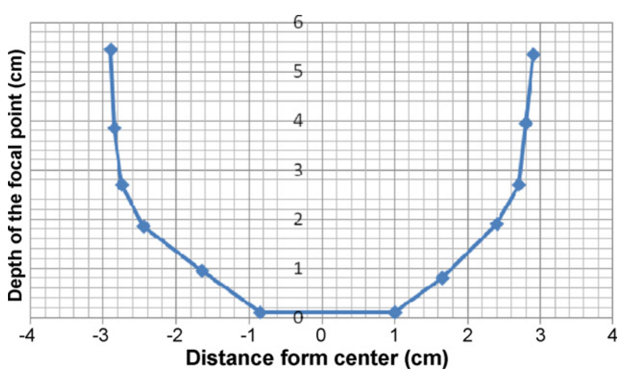

Fig. 7. The focal point measurement from the experiment setup.

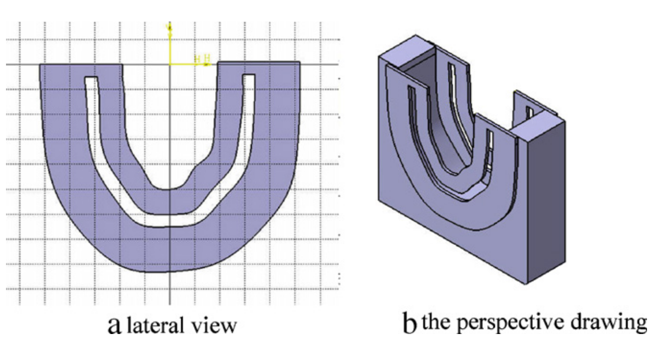

Fig. 8. Machined trajectory mechanism (the grid is 1 cm × 1 cm) (a) lateral view and (b) the perspective drawing.

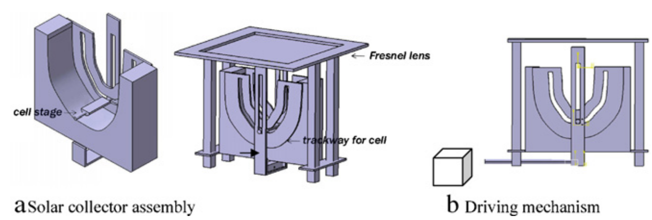

Fig. 9. Tracking mechanism assembly drawings.

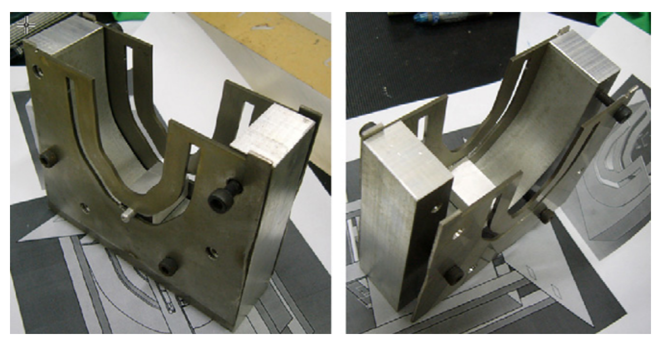

Fig. 10. The actual focal tracking mechanism assembly.

5. Experimental results

The system was first tested on the experimental simulator described in Section 3. As a reference, we also built a conventional single axis tracking device for testing the performance of the conventional tracking solar collection systems. We could not find a solar cell with the exact same size. The tests then included a $176 \times 118\,mm^2$ single crystal solar cell with 3 V 800 mA rated output. Table 3 compares the results with focal tracking collection and the conventional single axis tracking using the high efficiency but small GaAs multijunction cell and with the conventional single crystal silicon cell. Table 3 shows that comparing with the bare GaAs cell without lens and tracking, the conventional single axis tracking achieves an energy output of 2% while the focal tracking collection yields 39.2% energy output. The conventional single crystal silicon cell, even with the larger area ($176 \times 118\,mm^2/120 \times 120\,mm^2 = 1.44$), still produce less amount of energy output (3.654×10^{-2} vs. 3.686×10^{-2} kW h).

For the outdoor test results, Table 4 compares the performance of some of the available literatures with the proposed system. We are not sure about the result from [20], but the proposed system

Table 4
Outdoor solar collection efficiency test.

	Cell	Tracking	Concentration ratio	Power increase	Duration
Amonix [18]	Si	Y	500	30%	All day
Kemmoku [19]	InGaP/InGaAs/Ge	Y	300	50% (Si poly-crystal)	All day
Liao [20]	Si	Y	6	175%	All day
Focal tracking	GaAs	Y	144	40%	10:00–14:00

achieves higher or comparable power concentration efficiency to the other systems and yet, the proposed system can be built with no exposed moving part.

6. Conclusions

This research studied the possibility of a novel concentration solar collector. The proposed system moves the solar transducer instead of rotates the concentration lens. As a result, the proposed system might not achieve the highest conversion efficiency as the conventional concentration system, but it offers several advantages. First of all, the moving transducer carries far less mass than the concentrating lens. Secondly, the system allows the design of a system without exposed moving parts. In addition, it also enable vertical application rather than the flat wide open space application required by the conventional system. With a fix concentrating lens, the focal point moves along a strange trajectory as the sun move across the sky. This research presented the procedure to calculate the focal trajectory and designed a system that can track the trajectory. The experimental results showed that the proposed idea was feasible and the system achieved comparable performance to the conventional concentration solar collector.

Acknowledgements

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